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STUDIES ON EFFECT OF WELDING PARAMETERS ON THE FRICTION STIR WELDING OF ALUMINIUM 6061-T6 BUTT WELDED JOINTS USING TAGUCHI L9 APPROACH

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ABSTRACT

The two sheets of aluminum 6061-T6 alloy of size 200×150×3 (mm) are butt-welded by the friction stir welding process by varying the weld parameters such as rotational speed, tilt angle, and feed. The taguchi L9 experimental technique is used to draw the experimental conditions by taking the above said friction-stir welding process parameters. The temperature of the weld bead during the friction-stir welding is measured. The hardness of the weld bead is measured by using the hardness testing machine to find out the hardness value of the weld joints and on the base plates. Analysis of variance (ANOVA) analysis is performed to test the significance of the experimental model at 95% confidence interval. Optimality of the friction-stir welding process parameters for the butt welding of aluminum 6061-T6 alloy is obtained by using the multiple response desirability factors.

KEYWORDS: Aluminum 6061-T6 Alloy, Desirability factor, Friction Stir Welding, Response Temperature & Response Hardness

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Original Article

INTRODUCTION

A thin layer of oxide is present over the surface of aluminum which contains moistures. It reacts and forms oxide and releases hydrogen, which may cause porosity formation on the weld bead during the fusion welding. The strength of the weld joint will further reduce tremendously because of the presence of porosities on the weld bead. The high thermal conductivity of aluminium and its alloys is also a major problem for the fusion welding. The good weld-ability, mechanical and physical properties of aluminium 6061-T6, “a solution heat treated, then artificial aged alloy” made it a widely used material for the structural applications. The problem associated with the joining of aluminium 6061-T6 alloy by the fusion welding process can be overcome by the friction stir welding process. Friction stir welding is a solid state nature of the process in which coalescence produced by the heat obtained from the mechanically induced sliding motion or by the friction between two mating surfaces. A non consumable rotating tool attached with a special designed pin is getting inserted into the abutting edges of the two sheets which is to be joined. And when sufficient heat will be generated the rotating tool will traverse along the line of joint by creating the joining action of the two surfaces. The rotating tool performs two major functions that

are localized heating and the material flow. The rotating tool causes volumetric heating, so that a continuous joint is produced as the tool progressed in forward along the line of the joint. Welding begins by first plunging the rotating probe into the work pieces until the rotated shoulder came into close contact of the top surface of the work pieces.

The joining action of the two sheets took place by the localized heat generated by the rotating probe and the frictional heat produced by the movement of rotated shoulder along the line of the joint. As a result, there is no melting of the base metal and thus friction stir welding overcomes the fusion welding process in terms of solidification related defects. Design of experiment is a systematic and statistically tool to experiment on an unknown system or process by using the controllable and uncontrollable factors to obtain the optimized output and to make the hypothesis whether true or false. The various designs of experimental techniques are response surface methodology, Taguchi approach and factorial approach. The taguchi approach takes the mean value and signal to noise ratio to signify the experiment in terms of ANOVA analysis by calculating the variance presents in and within the experiment. Thus the aim addressed in this experiment is to test the temperature of the weld bead during the welding and hardness of the weld bead of the friction stir welded butt joints of aluminum 6061-T6 sheets by optimizing the friction stir welding process parameters using Taguchi L9 experimental approach.

In FSW problems, the HAZ objective function is developed and an auxiliary full factorial search is conducted to ensure Taguchi's orthogonal design assumption. The results confirm that the method can be successfully used for minimizing both the HAZ distance to the weld line and the peak temperature, with a minimal number of simulation runs via orthogonal arrays [1]. ANOVA and signal to noise ratio of robust design is used to optimize the process parameters and nonlinear regression analysis is used to develop a mathematical model to correlate the process parameters and measured tensile strength [2, 3]. Taguchi method was used to find the most important control factors which will yield higher tensile strength of the joints of friction stir welded dissimilar aluminium alloys [4, 5]. Plastic Size the materials. The weld produces at low speed have fine mechanical properties than weld produced at higher speed. There is a positive relationship between the axial load and tensile strength. If axial load increases tensile strength also increases [6]. Friction stir welding of aluminum alloy and High-density polyethylene sheets shows the improvement in welded joint quality by optimization of the process parameter. The main process parameters which affect the strength of the welded joint is tool rotational speed, welding speed, axial force and tool pin profile [7]. The FSW parameters such as tool rotation speed, welding speed, welding tool shoulder diameter, and welded plate thickness play a major role in determining the strength of the aluminum alloy joints [8]. The most influential control factors which will yield better tensile strength of the joints of friction stir welded RDE-40 aluminum alloy were determined by Taguchi approach [9, 10, and 11]. The L-9 and L-27 orthogonal arrays of Taguchi was used to analyze and determine the optimal condition, the results were put into S/N analysis and ANOVA to find the significant welding parameters affecting the weld quality [12, 13]. In FSW different types of tool, pin profiles were used to join aluminum alloys. It has been observed that the tool rotational speed exhibits more influence on tensile strength in both the tools [14]. A new friction stir vibration welding (FSVW) method is applied to modify the conventional friction stir welding (FSW) process. A fixture, which fixes the workpieces, is shaken mechanically during FSW in a direction normal to weld line in order to increase the straining of welds region material. This new process can be described as. Al 5052 alloy specimens are welded by two welding methods, FSW and FSVW. Metallography analyses indicate that grain size decreases and hardness increases and tensile test results also show that strength and ductility values of friction stir vibration (FSV)-welded specimens are greater than those relating to friction stir (FS)-welded specimens [15].

The influence of the main process parameters of the tool force, the micro- and macro mechanical properties, and the joints microstructures in the dip and hump zones were analyzed. The results showed that using the rotational speed change-based approach, the hump zones are subjected to increased heat input with consequent increase of the heat affected zone extension and average grain size (up to11 µm) [16]. The aluminum alloys were positioned on the top portion of the welding, creating a butt weld. The titanium alloy was placed on the bottom portion of the weld creating a lap welding with the aluminum alloy. On the aluminum side, residual stress and microhardness show a strong relationship the high value of residual stress resulted in a low value of microhardness. On the titanium side, residual stress shows a relation with temperature; the high value of temperature resulted in a low value of stress [17]. In the friction stir welding process, a large number of heat transfers to the spindle from the friction stir tools, resulting in low welding thermal efficiency and adverse impact on spindle bearings. Finite element numerical simulation used to investigate ten friction stir welding (FSW) tools with heat insulation features. It was found that the hollow tool design and smaller tool diameter significantly reduced the temperature of spindle tool holder [18]. A finite element model is utilized to calculate the fatigue, stress of the welding tool. Damage accumulation method and KBM multi-axial fatigue formulation are used to predict the fatigue life of the welding tool. Results indicate that the fatigue stresses on the tool pin are in tension on the front side and compression on the rear side [19].

EXPERIMENTAL DETAILS

Friction stir welding is produced at room temperature in a clean environment. Appropriate fixture is provided to hold the two sheets tightly together to prevent misalignment, distortion, and buckling. The ranges of the friction stir welding process parameters are rotational speed 560, 900, 1400 (RPM), tilt angle 0, 0.5, 1degree and feed 20, 63, 100 (mm/min). The circular probe is used to carry out the welding. Two sheets of aluminium 6061-T6 alloy of size 200×150×3 (mm) are butt welded by the friction stir welding by varying the above said parameters. The mechanical properties and chemical compositions of aluminium 6061-T6 alloy are given below in the table 1 and 2. The Taguchi L9 approach is used for the design and analysis of the experiment. The temperature of the weld bead during the friction stir welding is measured by the LASER gun. After the welding the welded pieces are tested for Dye penetrant inspection, which is found accepted. Then the hardness of the weld bead is measured with the help the hardness testing machine and tabulated below in the table 3. The complete friction stir welding setup is given below in figure 1.

Table 1: Chemical Compositions of Aluminium 6061-T6 Alloy (wt %)

Al	Mg	Si	Cr	Cu	Fe	Mn	Ti	Zn
95.8-98.6	0.80-1.2	0.40-0.80	0.04-0.35	0.15-0.40	<=0.7	<=0.15	<=0.15	<=0.25

Table 2: Mechanical Properties of Aluminium 6061-T6 alloy

Yield Strength	Ultimate Strength	Modulus of Elasticity	Poisson's Ratio	Elongation	Hardness (HB)
276 MPa	310 MPa	68.9 GPa	0.33	17%	95

(a) (b)

Figure 1: (a) Friction Stir Welding Setup (b) Circular probe

Table 3: Taguchi L9 Experimental Design and Results

Other parameter Probe - Circular							
S. No.	Rotational Speed (RPM)	Tilt Angle	Feed (mm/min)	Temperature at Bead	Temperature at Probe	Hardness Parent Metal	Hardness Weld Bead
1	560	0	20	127	170	103	71.62
2	560	0.5	63	148	178	103	73.62
3	560	1	100	144	188	103	84.92
4	900	0	63	114	183	88	79.03
5	900	0.5	100	121	175	103	84.54
6	900	1	20	141	177	95	89.08
7	1400	0	100	105	174	103	73.24
8	1400	0.5	20	139	186	95	71.58
9	1400	1	63	144	171	95	82.49

Figure 2: A 09 Numbers of Friction Stir Welded Joints using Circular Probe

RESULT AND DISCUSSIONS FOR THE RESPONSE TEMPERATURE

Taguchi experimental design is used for the experiment where 09 experimental conditions were generated considering three factors at three levels to identify the effects of process parameters and circular probe to the weld. The experiment is performed randomly to eliminate errors if any present in the machine. The adequacy of the developmental relationship is evaluated using the analysis of variance technique (ANOVA) shown below in the table 4 in response mean and table 5 for a response SN ratio for temperature at the weld bead measured during the welding. ANOVA helps to identify the effect of each factor versus the objective function and it also determines the total variation present in the model. In this technique, if the calculated F value, i.e. 0.0068 and 0.0076 of the developed model is less than the standard F-ratio (from F-table) i.e. 0.05 value at a desired level of confidence (95%), the model is said to be adequate within the

confidence limit and termed as significant. The degrees of freedom of the model are the number of parameters used to fit the model with the experimental output. The sum of squares is the difference between the response values and the sample mean. The sum of squares represents the total variations in the response values of the model. The mean square is the ratio between the sum of squares and corresponding degrees of freedom. The summary of fit shown below in the tables6 and 7 of response means and SN ratio of the measured temperature describes that if the R Square is 0.99, then the experimental output fits to the experimental model well. An RSquare closer to 1 indicates a better fit to the data than does an RSquare closer to 0. An RSquare near 0 indicates that the model is not a much better predictor of the response than the response mean. Root mean square error shows the estimation of the standard deviation of the random error. Mean shows the overall mean of the response values.

Table 4: Analysis of Variance for the Response Mean of Temperature at Weld Joint

Source	Degrees of Freedom (DF)	Sum of Squares	Mean Squares	F Ratio	Whether Significant or Not
Model	6	1866.0000	311.00	147.31	Yes
Error	2	4.22	2.111	Prob.>F 0.0068*	
Total	**8**	**1870.22**			

Table 5: Analysis of Variance for the Response SN Ratio of Temperature at Weld Joint

Source	Degrees of Freedom (DF)	Sum of Squares	Mean Squares	F Ratio	Whether Significant or Not
Model	6	8.81	1.469	130.63	Yes
Error	2	0.022	0.011	Prob.>F 0.0076*	
Total	**8**	**8.84**			

Table 6: Summary of Fit for the Response Mean of Temperature at Weld Bead

R Square	0.997
R Square Adjust	0.99
Root Mean Square Error	1.45
Mean of Response	131.44
Observations	9

Table 7: Summary of Fit for the Response SN Ratio of Temperature at Weld Bead

R Square	0.997
R Square Adjust	0.98
Root Mean Square Error	10.106
Mean of Response	42.31
Observations	9

The effect test results only present when there are fixed effect in the model which is shown below in the tables 8 and 9 for the response mean and SN ratio of the measured temperature. The significance of Prob. > F shows that there is the individual effect of each welding process parameters such as rotational speed, tilt angle and feed on the temperature at weld bead measured during the friction stir welding. The Nparm shows the number of parameters associated with the effect of all the process parameters on the response temperature.

Table 8: Result for Effect Test for the Response Mean of Temperature at Weld Bead

Source	N parm	DF	Sum of Squares	F Ratio	Prob.> F	Whether Significant or Not
Rotational speed	2	2	328.22	77.73	0.0127*	Yes
Tilt angle	2	2	1241.55	294.05	0.0034*	Yes
Feed	2	2	296.22	70.15	0.0141*	Yes

Table 9: Result for Effect Test for the Response SN Ratio of Temperature at Weld Bead

Source	N parm	DF	Sum of Squares	F Ratio	Prob.> F	Whether Significant or Not
Rotational speed	2	2	1.50	66.76	0.0148*	Yes
Tilt angle	2	2	5.84	259.63	0.0038*	Yes
Feed	2	2	1.47	65.51	0.0150*	Yes

The table 10 and 11 for the response mean and the SN ratio of the measured temperature shown below describes the scaled estimation of process parameters to identify the individual effect and their significance of values of process parameters on the measured temperature. The significance of the prob. >t i.e. <.0001*shows that there is an interaction effect of the process parameters on the response. The t-ratio is the ratio of the parameter estimate of its parametric standard error. The term rotational speed 1400 RPM is not a significant parameter because of it does not satisfy the 95% confidence interval by the value 0.091 which is greater than prob. > t 0.05, whereas all other process parameters values are satisfies the 95% confidence interval and termed as significant.

Table 10: Scaled Estimations of Process Parameters for the Response Mean of Temperature

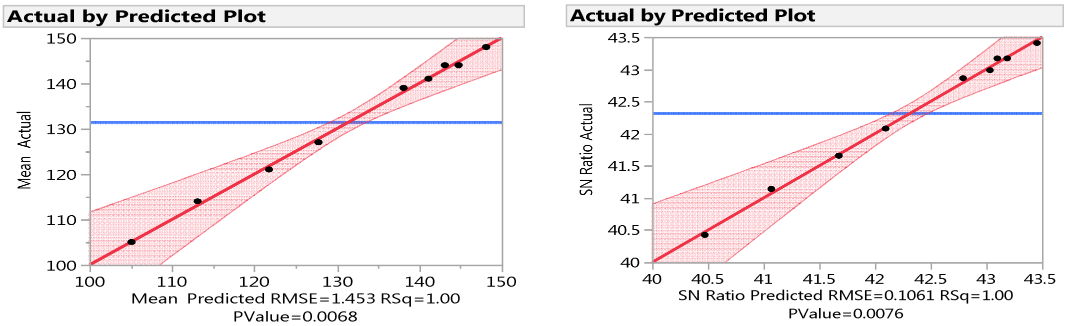
Term	Scaled Estimates	Standard Error	t Ratio	Prob.> [t]	Whether Significant or Not
Intercept	131.44	0.484	271.4	<.0001*	Yes
Rotational speed [1400]	-2.11	0.68	-3.08	0.0911	No
Rotational speed [560]	8.22	0.68	12.0	0.0069*	Yes
Rotational speed [900]	-6.11	0.68	-8.92	0.0123*	Yes
Tilt angle [0]	-16.11	0.68	-23.52	0.0018*	Yes
Tilt angle [0.5]	4.55	0.68	6.65	0.0219*	Yes
Tilt angle [1]	11.55	0.68	16.87	0.0035*	Yes
Feed [100]	-8.11	0.68	-11.84	0.0071*	Yes
Feed [20]	4.22	0.68	6.16	0.0253*	Yes
Feed [63]	3.88	0.68	5.68	0.0296*	Yes

Table 11: Scaled Estimations of Process Parameters for the Response SN Ratio of Temperature

Term	Scaled Estimate	Standard Error	t Ratio	Prob.> [t]	Whether significant or not
Intercept	42.32	0.0353	1197.02	<.0001*	Yes
Rotational speed [1400]	-0.16	0.0499	-3.39	0.0772	No
Rotational speed [560]	0.56	0.0499	11.26	0.0078*	Yes
Rotational speed [900]	-0.39	0.0499	-7.87	0.0157*	Yes
Tilt angle [0]	-1.1	0.0499	-22.14	0.0020*	Yes
Tilt angle [0.5]	0.32	0.0499	6.41	0.0235*	Yes
Tilt angle [1]	0.78	0.0499	15.73	0.0040*	Yes
Feed [100]	-0.57	0.0499	-11.42	0.0076*	Yes
Feed [20]	0.32	0.0499	6.41	0.0253*	Yes
Feed [63]	0.25	0.0499	5.01	0.0376*	Yes

The correlation between the actual and the predicted values are presented by the correlation graph below in figure 3. The desirability factor in figure 4 describes that the whether the mean and the SN ratio of the process parameters are

desirable to the experimental conditions of friction stir welding of aluminium 6061-T6 alloy. It shows the maximum desirability of a particular parameter among all other parameters taken for the experiment. The maximum desirability of optimized parameters, is found 99%, when the rotational speed 560 RPM, tilt angle 1 degree and feed is 20 mm/min. Desirability factor is used for multiple response optimizations to find out the optimum condition of the process parameters in relation to the multiple responses.



(a) (b)

Figure 3: (a) Actual by predicted plot of the Response Mean (b) Response SN Ratio for Temperature

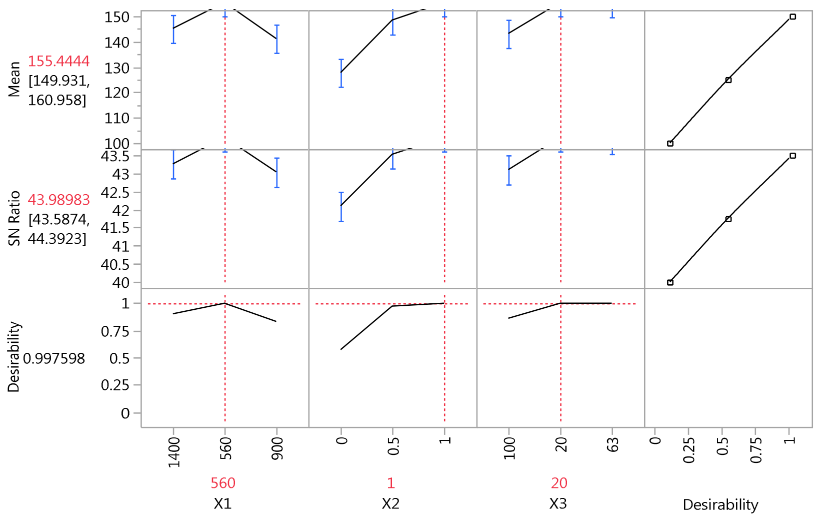


Figure 4: Desirability Factor of Weld Parameters in Response to the Mean and SN Ratio for Temperature

RESULT AND DISCUSSIONS FOR THE RESPONSE HARDNESS

The hardness is measured on the weld bead by creating an indentation mark with the help of a diamond ball indenter. The depth of the indentation mark is measured and hardness value is presented in the experimental table 3. The obtained hardness results are then analyzed by taking analysis of variance which is a statistical tool used to measure the significance of the experimental model terms. The summary of fit on the table 12 and 13 given below describes the mean and the SN ratio of the response measured hardness of the weld joint in which the R square value is 0.99 which represents the experiment outputs i.e. hardness results is well fitting to the experimental model.

Table 12: Summary of fit for the Response Mean of Hardness of the Weld Joint

RSquare	0.994
R Square adjust	0.97
Root mean square error	0.978
Mean of response	78.902
Observations	9

Table 13: Summary of Fit for the Response SN ratio of Hardness of the Weld Joint

RSquare	0.993
RSquare Adj.	0.97
Rootmean square error	0.112
Mean of response	37.914
Observations	9

The table 14 and 15 shown below is the representation of analysis of variance for the response mean and SN ratio of obtaining hardness values of the weld joint. The experimental model is significant for the reason of F ratio 0.00163 and 0.0180 values are less than 0.05 therefore it satisfies the conditions of 95% confidence level.

Table 14: Analysis of Variance for the Response Mean of Hardness of Weld Joint

Source	Degrees of Freedom (DF)	Sum of Squares	Mean Squares	F Ratio	Whether Significant or Not
Model	6	349.16	58.19	60.73	Yes
Error	2	1.91	0.958	Prob>F 0.0163*	
Corresponding total	8	351.08			

Table 15: Analysis of Variance for the Response SN Ratio of Hardness of Weld Joint

Source	Degrees of Freedom (DF)	Sum of Squares	Mean Squares	F Ratio	Whether Significant or Not
Model	6	4.19	0.699	54.87	Yes
Error	2	0.025	0.012	Prob>F 0.0180*	
Corresponding total	8	4.22			

The table 16 and 17 shows the results of the effects of process parameters such as rotational speed, tilt angle and feed and their significance level whether the parameters satisfies the 95% confidence level or not. For the response hardness the process parameter rotational speed and tilt angle is significant where as the feed does not satisfy the conditions of 95% confidence level and thus termed as insignificant.

Table 16: Result for Effect test for the Response Mean of Hardness of Weld Joint

Source	Nparm	Degrees of Freedom (DF)	Sum of Squares	F Ratio	Prob.> F	Whether Significant or Not
Rotational speed	2	2	128.4	67.02	0.0147*	Yes
Tilt angle	2	2	201.3	105.02	0.0094*	Yes
Feed	2	2	19.3	10.08	0.0902	No

Table 17: Result for Effect Test for the Response SN Ratio of Hardness of Weld Joint

Source	Nparm	Degrees of Freedom (DF)	Sum of Squares	F Ratio	Prob.> F	Whether Significant or Not
Rotational speed	2	2	1.54	60.53	0.0163*	Yes
Tilt angle	2	2	2.39	93.99	0.0105*	Yes
Feed	2	2	0.257	10.07	0.0903	No

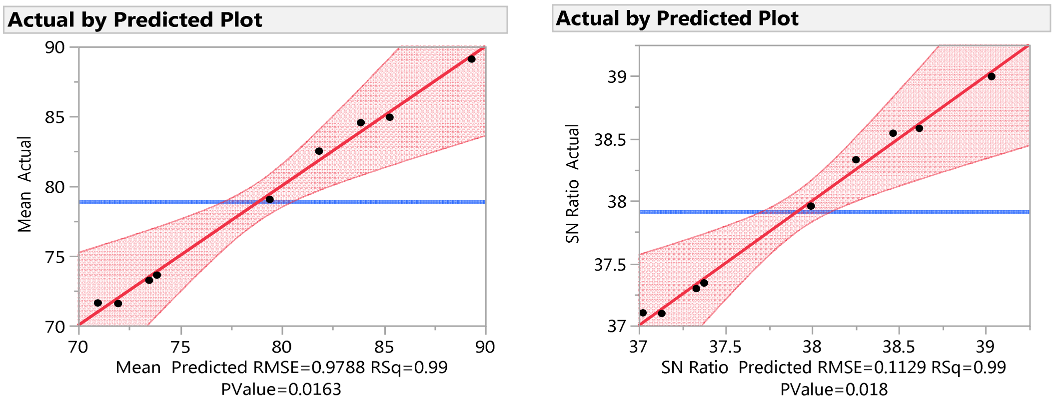
Table 18: Scaled Estimations of Process Parameters of the Response Mean of Hardness Values

Term	Scaled Estimate	Standard Error	t Ratio	Prob.> [t]	Whether Significant or Not
Intercept	78.9	0.326	241.82	<.0001*	Yes
Rotationalspeed [1400]	-3.13	0.0461	-6.79	0.0210*	Yes
Rotational speed [560]	-2.18	0.0461	-4.73	0.0419*	Yes
Rotational speed [900]	5.31	0.0461	11.52	0.0075*	Yes
Tilt angle [0]	-4.27	0.0461	-9.26	0.0115*	Yes
Tilt angle [0.5]	-2.32	0.0461	-5.03	0.0373*	Yes
Tilt angle [1]	6.59	0.0461	14.29	0.0049*	Yes
Feed [100]	1.99	0.0461	4.33	0.0494*	Yes
Feed [20]	-1.47	0.0461	-3.20	0.0854	No
Feed [63]	-0.52	0.0461	-1.13	0.3752	No

Table 19: Scaled Estimations of Process Parameters for the Response SN Ratio of Hardness Values

Term	Scaled Estimate	Standard Error	t Ratio	Prob.> [t]	Whether Significant or Not
Intercept	37.91	0.376	1007.24	<.0001*	Yes
Rotational speed [1400]	-0.34	0.0532	-6.42	0.0234*	Yes
Rotational speed [560]	-0.24	0.0532	-4.53	0.0455*	Yes
Rotational speed [900]	0.58	0.0532	10.95	0.0082*	Yes
Tilt angle [0]	-0.46	0.0532	-8.72	0.0129*	Yes
Tilt angle [0.5]	-0.25	0.0532	-4.8	0.0407*	Yes
Tilt angle [1]	0.71	0.0532	13.52	0.0054*	Yes
Feed [100]	0.22	0.0532	4.21	0.0521	No
Feed [20]	-0.18	0.0532	-3.46	0.0745	No
Feed [63]	-0.04	0.0532	-0.75	0.5298	No

The hardness is measured on the weld bead by creating an indentation mark with the help of a diamond ball indenter. The depth of the indentation mark is measured and hardness value is presented in the experimental table 3. The obtained hardness results are then analyzed by taking analysis of variance which is a statistical tool used to measure the significance of the experimental model terms. The summary of fit on the table 12 and 13 given below describes the mean and the SN ratio of the response measured hardness of the weld joint in which the R square value is 0.99 which represents the experiment outputs i.e. hardness results is well fitting to the experimental model.



(a) (b)

Figure 5: (a) Actual by Predicted plot of the Response Mean (b) Response SN Ratio for Hardness Values

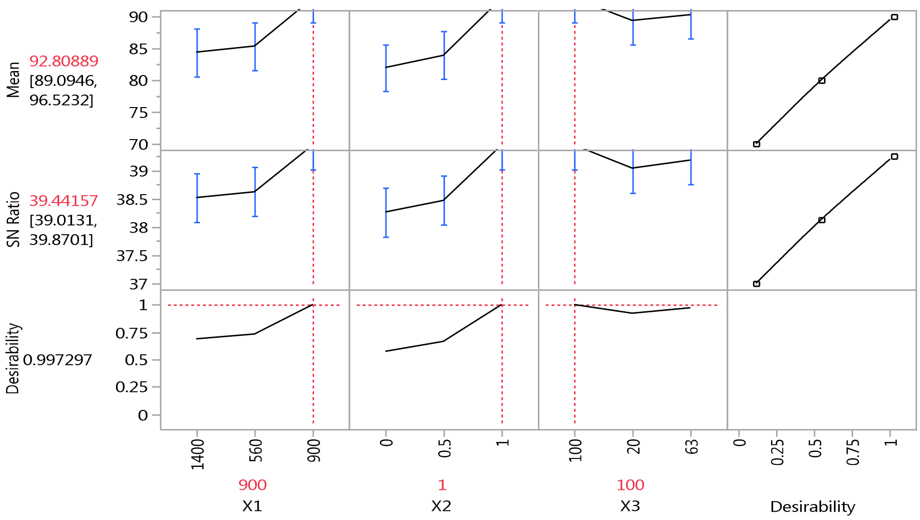


Figure 6: Desirability Factor of Weld Parameters in Response to the Mean and SN Ratio of Hardness Values

CONCLUSIONS

- The aluminum 6061-T6 alloy is successfully welded by the friction stir welding and the response temperature, hardness of the weld bead is measured.
- It is found from the ANOVA analysis that the experimental model is a significant model. The optimized parameters for the response temperature of the friction stir welded aluminum 6061-T6 alloy sheets are rotation speed 560 RPM, tilt angle 1 degree and feed 20 mm/min with the maximum desirability of 99%.
- The optimized parameters for the response hardness values of the friction stir welded aluminum 6061-T6 alloy sheets are rotation speed 900 RPM, tilt angle 1 degree and feed 100 mm/min with the maximum desirability of 99%.
- There is the major effect of rotational speed on the friction stir welding of the aluminum 6061-T6 alloy sheets whereas the process parameter feed having the minor effects and feed depends upon the rotational speed. The effect of tilt angle is small and applicable for certain applications.

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